Initial Jupiter Orbit Insertion and Period Reduction Maneuver Plans for Juno

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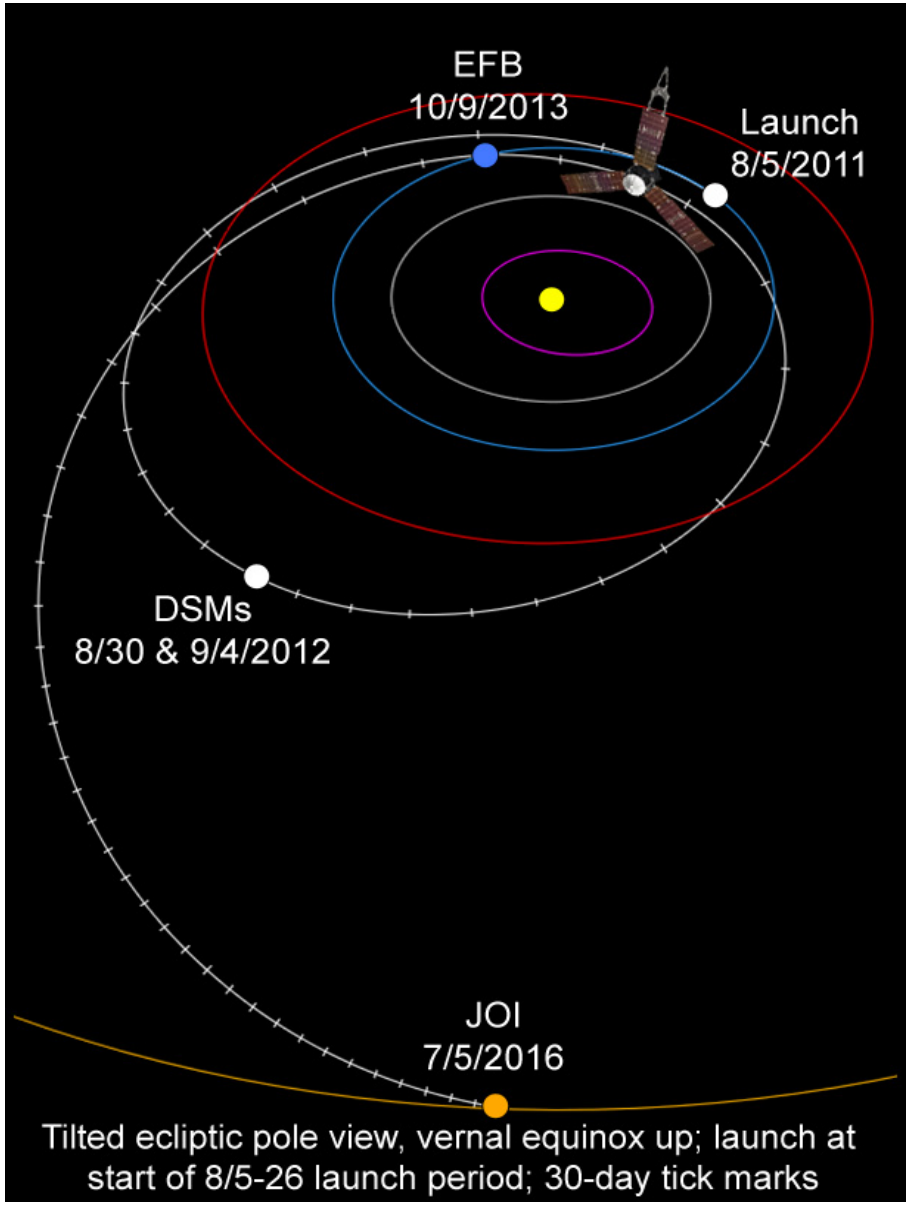
Agenda

- Interplanetary trajectory and Jupiter orbital plans at launch
- Safing events after Earth flyby and redesign of Jupiter mission
- Development of new reference trajectory with14-day orbits and two 53.5-day "characterization" orbits between JOI and PRM burns
- Contingencies analyzed for JOI burn
  - Delayed start or interrupted JOI burn
  - JOI burn terminated by timer cutoff
- PRM contingencies

Plans at Launch for Orbital Mission



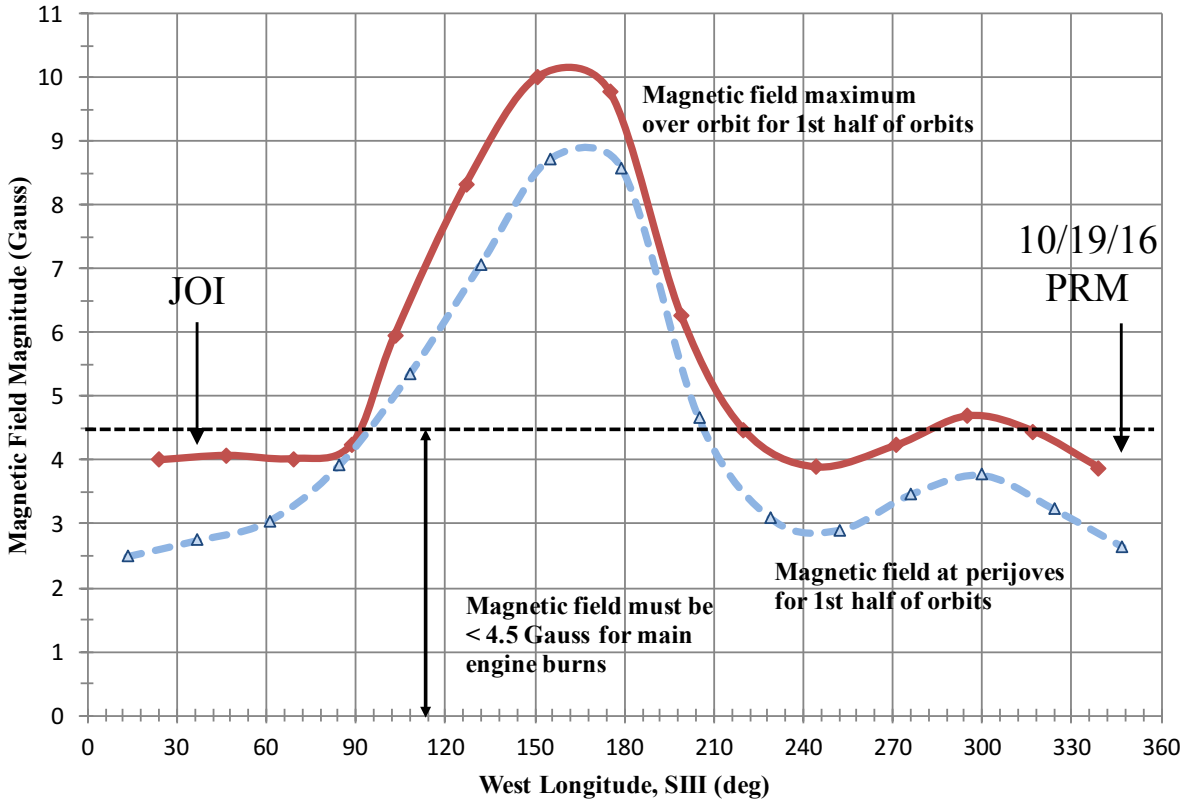
- Solar-powered, spin stabilized spacecraft
- 2+ DV-EGA Trajectory
  - Launch, August 2011
  - DSMs split into two parts (main engine qualified for max. 42 min burn duration)
  - Earth flyby at 550 km altitude; "practice" for perijove; included 20-min eclipse
- Jupiter Orbit Insertion (JOI) to 107-day polar capture orbit
- Period Reduction Maneuver (PRM), Oct. 19, 2016, to 11-day orbits
  - Low-altitude perijoves centered over Goldstone view period for gravity science
  - 192º spacing between subsequent equator crossings for magnetic field investigation
    - 30 orbits give 12º spacing
    - 1 extra orbit
  - Deorbit into Jupiter late Oct. 2017
- Study atmosphere, gravity, magnetosphere
- High radiation environment

Safings, Side-Swap and Need for Redesign

- Spacecraft safings after Earth flyby
  - Near end of eclipse (battery low voltage); SRU-1 marked failed (stellar reference unit state not cleared at exit from safe mode); Sun-Earth tag-up timer not reset
- Side swap six months later
  - Invalid instruction address (memory corruption); task not responding to aliveness "pings" (priority given to data salvage task that ran too long)
- Concern that surprises in radiation/magnetic field environment might cause safing event(s) and lose one or more perijoves before recovery.
  - Only one additional orbit in 11-day mission to recover from a missed longitude.
  - Radiation dosage building fast for second half of orbits
- Began redesign effort involving capture orbit and orbital mission
  - Split the capture orbit into 2 or 3 orbits to provide early science and checkout of science instruments; instruments not on during orbits with JOI or PRM
  - Longer orbit between perijoves could better deal with potential anomalies at Jupiter

New Capture Orbit Period: Different PRM Epoch?

- Changing the capture orbit period likely means a change to the PRM epoch.
- Not all potential PRM dates are acceptable because of high magnetic field magnitude.
- Changing PRM epoch changes the longitude by:
- 870.536°/day * 0.9975 day for each day change in PRM
  = Jupiter rotation rate * 1/400 days (Earth-Jupiter synodic period ~ 400 days)
- JOI max. burn duration 42 min

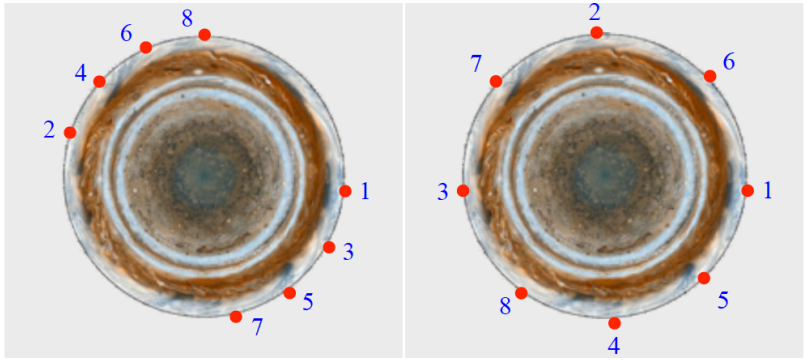


- More radiation for 2 or 3 orbits
- Project decided on 53.5 day orbit; retains original PRM date
- PJ1 not over Goldstone

Longitude Cadence Important for Orbital Mission

- Considerations for orbit period redesign:
  - Longitude spacing between successive orbits:
    870.536º/day * 0.9975 days * integer-days (rounded off to "nice" value)
  - Desire coarse mapping (repeat pattern) then finer mapping
  - Longitude order: Good to cover different parts of Jupiter early in mission
  - 14-day, 21-day, 28-day orbits synch up well with human 7-day work week
  - Maneuver size to maintain equator crossing longitude targets
  - Altitude at perijoves (3100 to 8000 km)
  - Ease/difficulty in placing perijove science within Goldstone DSS-25 view period
  - Number of orbits needed for final mapping (at least 30 orbits)
  - Mission length and cost
  - Radiation dosage

1st 8 orbits of
11-day period case,
192º w. long. spacing:
15 orbits coarse grid,
30 orbits to complete grid

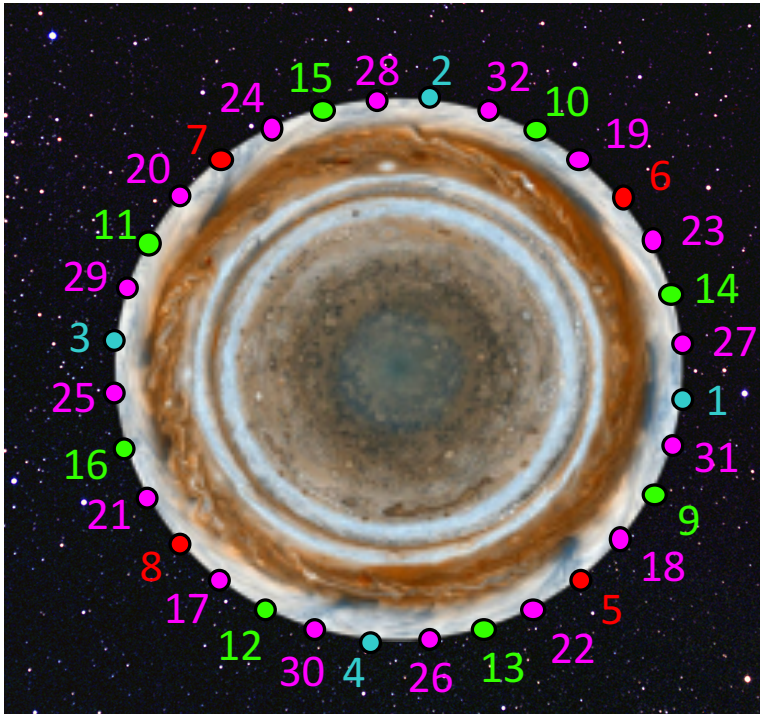


1st 8 orbits of
14-day period case
270º w. long. spacing:
4 orbits coarse grid,
8, 16 orbits finer grids,
32 orbits to complete grid

14-day Orbits Chosen for Reference Mission

- PRM on Wednesday (10/19/16) + 14-day orbits → Wednesdays for early orbit numbers for perijoves and orbit trim maneuvers (transitioning to Tuesdays over mission)
- 270º between successive equator crossings
- Pattern repeats every 4 orbits; need shifts in longitude are made to fill out grid
  - 4 orbits: 90º spacing
  - 8 orbits: 45º spacing
  - 16 orbits: 22.5º spacing
  - 32 orbits: 11.25º spacing

- Larger maneuvers needed to maintain desired longitude spacing but deemed manageable with propellant available for contingencies
  - JOI
  - PRM
  - Backup maneuvers



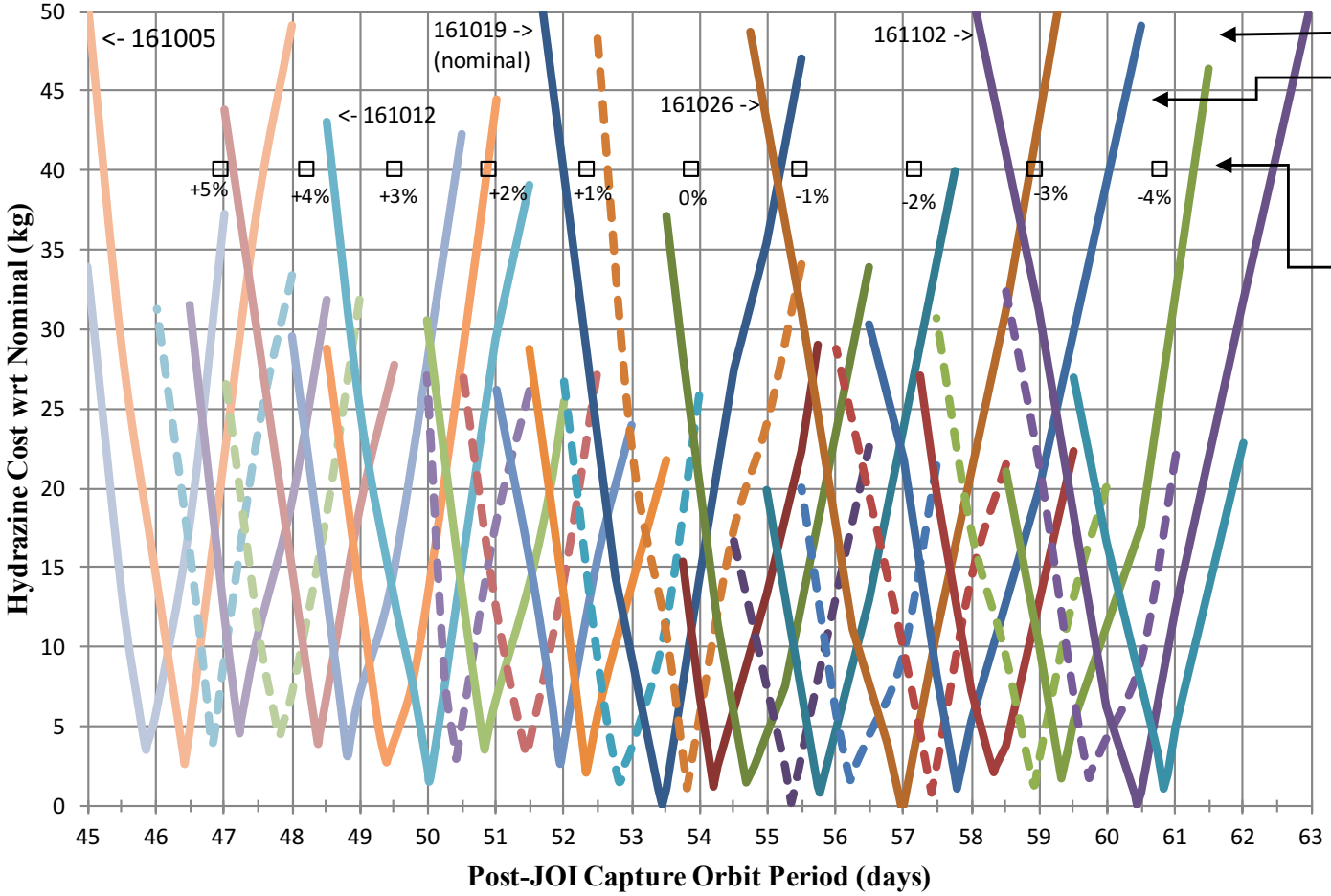
JOI Contingencies

- JOI is a critical event
  - 35-min nominal duration for 53.5-day capture orbit
  - 25 min and no restart gives ~6-month orbit
  - 22.5 min and no restart gives ~1 year orbit
- Auto restart capability enabled for main engine (500-sec wait, multiple restarts possible), most other fault protection responses disabled
- Recovery from a JOI burn anomaly involves
  - Determining actual capture orbit period, then
  - Determining another PRM epoch (usually 2 times the capture orbit period from JOI epoch) which has low magnetic field magnitude and
  - Resetting starting longitude value to center over Goldstone view period and developing sequence of longitudes and shifts to fill out grid pattern for 14-day mission
- Guidelines for JOI recovery
  - Retain nominal PRM epoch if possible
  - Change to PRM epoch which is +/- 14 days wrt nominal to preserve much of science planning
  - Change to PRM epoch which is +/- 7 days wrt nominal to preserve Wednesday perijoves
  - Change to nearby PRM epoch (with acceptable magnetic field magnitude).
  - Limit hydrazine cost for recovery to 25 kg, although could have higher cost for preserving nominal PRM epoch or having PRM epoch be +/- 7 days or +/- 14 days wrt nominal.

JOI Contingencies Analyzed

- JOI burn anomalies considered in detail:
  - Interrupted burn (especially single 500-sec interruption) with restart ,
  - Burn terminated on timer cutoff
- Recovery from interrupted JOI burn
  - 500-sec interruption lengthens capture orbit period by 4.3 days at start of burn and 7.9 days just before middle of burn.
    - Optimal recovery cost is 7 to 15 kg of hydrazine for acceptable PRM dates
    - Cost to retain Wednesday perijoves (PRM date changed by multiple of 7 days) is ~ 43 kg.
    - Can retain nominal PRM date at cost of 30 kg only if (single) interruption occurs more than 33 min into 35-min burn.
- Redesigns for JOI burn terminated on timer cutoff
  - Values of +/- 1% to 2% normally expected based on main engine and IMU performances
  - Timer cutoff values set large (roughly -4% to +5%) so that in worst case, capture orbit period could be 7 days smaller (termination at timer max.) or 7 days larger (termination at timer min. value); PRM dates would be 14 days earlier or later, respectively.
  - Cost to retain Wednesday perijoves could be up to 50 kg for timer cutoff cases.
  - Optimal cost is much lower to change to different PRM date, < 20 kg.
- Plotting hydrazine cost for recovery with different PRM dates vs post-JOI orbit period summarizes wide variety of contingency scenarios. (See next slide.)

Hydrazine Cost to Recover from JOI Anomaly



PRM dates at +/- 14 days and +/- 7 days wrt nominal epoch (to retain Wednesday perijoves); hydrazine cost can be 50 kg.

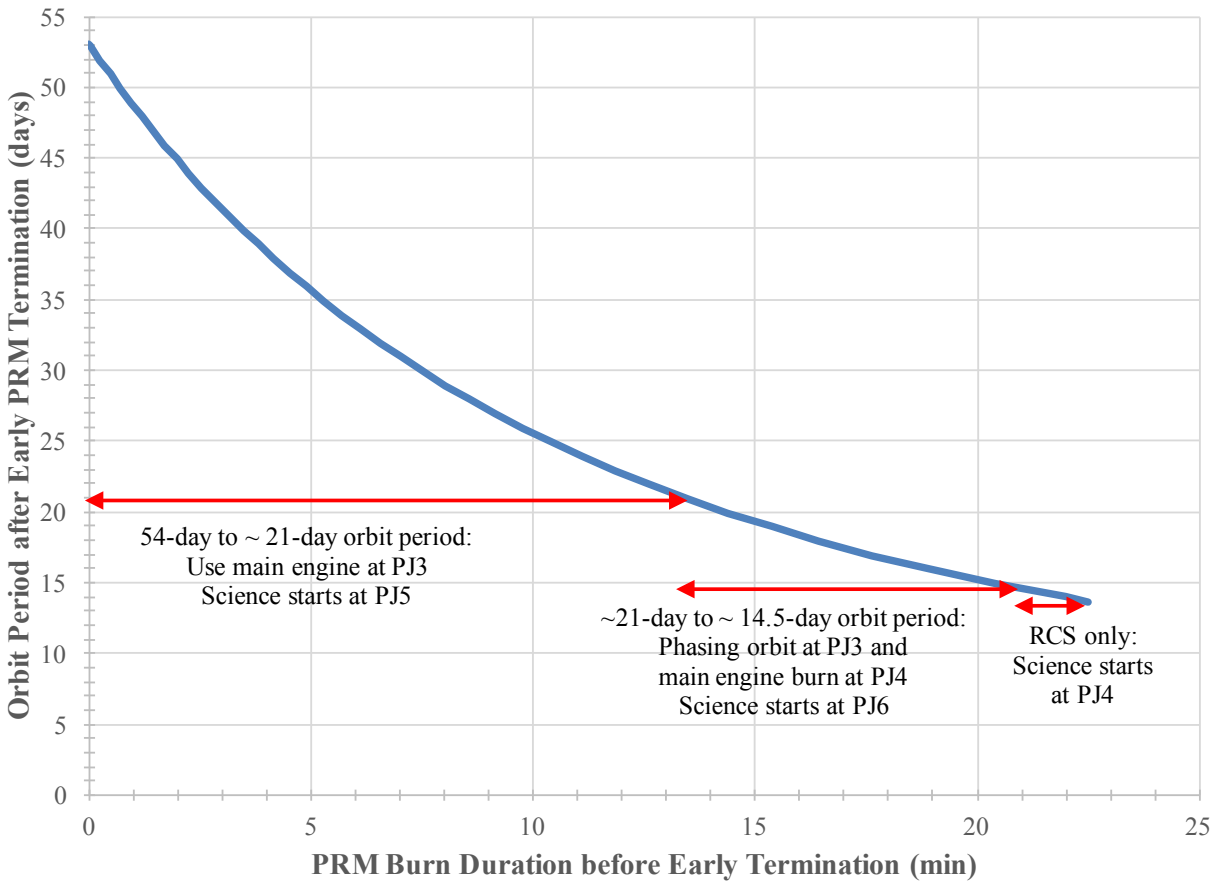
Corresponding timer cutoff values.

Over/ Under Burn %	JOI Burn Duration (min)	Orbit Period (days)
-4	33.6	60.8
-3	34.0	58.9
-2	34.3	57.2
-1	34.7	55.5
0	35.0	53.9
1	35.4	52.3
2	35.7	50.9
3	36.1	49.5
4	36.4	48.2
5	36.8	47.0

No PRM on dates with dashed lines because magnetic field magnitude is too high, i.e, > 4.5 gauss. Cost < 20 kg for optimal PRM dates.

What if PRM Terminates Early?

- PRM has no restart capability and is not considered to be a critical event because an additional main engine burn could be made on a subsequent perijove (1 additional regulated main engine burn possible).
- Select PRM#2 date depending on period achieved and low magnetic field magnitude criteria.



- If PRM terminates early and another main engine burn is NOT possible, can adjust orbit period to nearby value to place perijoves over Goldstone and give a longitude grid map.
- Options available for different grid depending on post-PRM orbit; would use process similar to that for the 14-day redesign.
- Several transition orbits with RCS thrusters would likely be required.

Concluding Remarks

- Juno project was well prepared to handle contingencies for JOI and PRM main engine burns.
- JOI execution was flawless.
- About a week before the PRM burn, the project noticed an issue with the pressurization of the main engine and called off the burn.
- The project has since decided to remain in the current 53-day orbit rather than perform another main engine burn.
- The trajectory design for the new reference mission is described in paper by Tom Pavlak.